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MASTER

AEROSOLS AND SOLAR ENERGY

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Abstract

A brief description is presented of the involvement of the Solar Energy Research Institute (SERI) in atmospheric research, including aerosol characterization and modeling. The use of both rigorous and simple models for radiation transport is described. Modeled broadband solar irradiance data are shown to illustrate the important influence that aerosols have on the energy available to solar systems and the economics of solar systems design. Standard aerosol measurement methods for solar applications are discussed along with the need for improved instrumentation and methods.

INSOLATION RESOURCE ASSESSMENT PROGRAM

The national program for insolation resource assessment is administered for the Department of Energy (DOE) by the Solar Energy Research Institute (SERI). This program is run by the Energy Resource Assessment Branch (ERAB) at SERI. This branch has the responsibility of:

- providing accurate insolation resource assessments, models, and databases to DOE, other SERI programs, utilities, industry, and the public;
- evaluating the developing improved insolation resource characterization models, databases, and instrumentation;
- investigating the feasibility of forecasting solar energy on a mesoscale basis for solar energy applications; and
- program management.

The insolation area encompasses data collection, construction of models, energy forecasting, and advanced instrument development for solar energy measurements.

INSOLATION MEASUREMENTS PROGRAMS

The National Oceanic and Atmospheric Administration (NOAA) manages a network of 38 insolation measurement sites. At most of these sites, direct insolation and global insolation on a horizontal surface are collected on a daily basis. ERAB at SERI works closely with the personnel involved with this network. SERI currently has a database called SOLMET that was collected at 26 historical sites, and the data from the new sites will be obtained as it becomes available. This database will be available through NOAA-NCC to energy data users.

DOE has eight Solar Energy Research and Training Sites located at universities in eight different regions of the country. ERAB assists DOE in providing management support for these sites. This includes technical review of proposals, reports, and papers generated by the projects and making recommendations concerning progress, content, and direction.

ERAB is currently involved in establishing an Insolation Research Laboratory at the SERI site near Golden, Colorado. This laboratory will have more than 50 pyranometers measuring insolation at various orientations and within different spectral bands. Also, several pyrheliometers will measure the direct component of the insolation. Included in these devices will be an active cavity pyranometer and an active cavity pyrheliometer to be used as standards. A solar spectroradiometer is being built for this laboratory that will be capable of making absolute spectral measurements between 0.3 and 2.65 μm wavelength in a continuous scan mode. This device will measure direct, diffuse, and total global insolation during separate scans. A circumsolar telescope [1] with many automatic features will be located at this facility. This instrument scans $\pm 3°$ from the sun's center and has an angular resolution of 1.5 minutes of arc out to two solar radii and 5 minutes of arc from there to 3°. Other instrumentation that is currently planned for this site includes a solar photometer to measure turbidity and atmospheric water vapor, one or more aerosol particle systems to measure particle size distribution at the surface, and various types of solar trackers and data logging systems.

ATMOSPHERIC MODELING RESULTS

The relative effect of various atmospheric constituents on atmospheric transmittance of solar energy has been investigated using a modified version of a LOWTRAN [2] computer code. This modified version, called SOLTRAN, has incorporated the extraterrestrial solar spectrum of Thekaekara [3] and the capability of integrating over the total spectral transmittance to obtain broadband transmittance. Integration over the spectral transmittance due to H_2O, O_3, CO_2 plus O_2, Rayleigh scattering, and aerosol extinction also has been incorporated so that the relative broadband effect of each atmospheric constituent can be determined.

The SOLTRAN model constructs a 33 layer atmosphere with the number density of each constituent and the temperature and pressure defined at each layer. This model accommodates effects due to earth curvature and index of refraction changes. A band model for molecular absorption is used that is based on laboratory transmittance data and available molecular line constants. This atmospheric model is illustrated in Fig. 1.

Results of applying the SOLTRAN model are shown in Figs. 2 and 3 for a Midlatitude Summer (MLS) and a Subarctic Winter (SAW) atmospheric model, respectively. These atmospheric models are two of six standard atmospheres that can be selected in the program with the additional capability of forming an atmosphere from radiosonde data. These atmospheres were chosen because they are representative of the atmospheric content of H_2O and O_3 that are expected in the United States. The MLS model atmosphere contains 2.93 cm of H_2O and 0.31 cm of O_3, and the SAW model atmosphere contains 0.42 cm of H_2O and 0.45 cm of O_3. Both figures are for a continental type aerosol with a sea-level visibility of 23 km. An aerosol with a sea-level visibility of 23 km is considered to be a fairly clear atmosphere. These results illustrate the relative importance of each atmospheric constituent, and they also emphasize the importance of aerosols in solar radiation transport modeling. Aerosol attenuation appears to dominate all other constituents. Unfortunately, the aerosol is the constituent that is the most difficult to characterize and is, therefore, the least well defined for solar applications.

The SOLTRAN model has been used to make comparisons with some very simple direct insolation models [4-7]. An example of a comparison for H_2O only is shown in Fig. 4. The data illustrated by the triangles was a simple model generated by one of the authors by fitting an expression to the SOLTRAN results. By performing a study of this type for each atmospheric constituent and the total atmospheric transmission one can, hopefully, arrive at an optimum simplified model that can be used by solar systems designers.

SERI also has a rigorous model that includes the effects of multiple order scattering and ground reflection [8-9]. This model uses Monte Carlo techniques to solve the equation of radiative transfer. This technique utilizes statistical methods to follow one photon at a time on its three-dimensional path through the atmosphere. Figure 5 illustrates this model. The model is operational and has been used to generate insolation data. The model will be used to study various atmospheric phenomena such as the solar aureole due to aerosol scattering in the forward direction. In addition, a comparison of results from this model is being made with existing simplified models for total global insolation.

The importance of modeling accuracy and accuracy of measurements on atmospheric constituents, such as aerosols, can best be shown by the effect of uncertainties in insolation on solar system design.

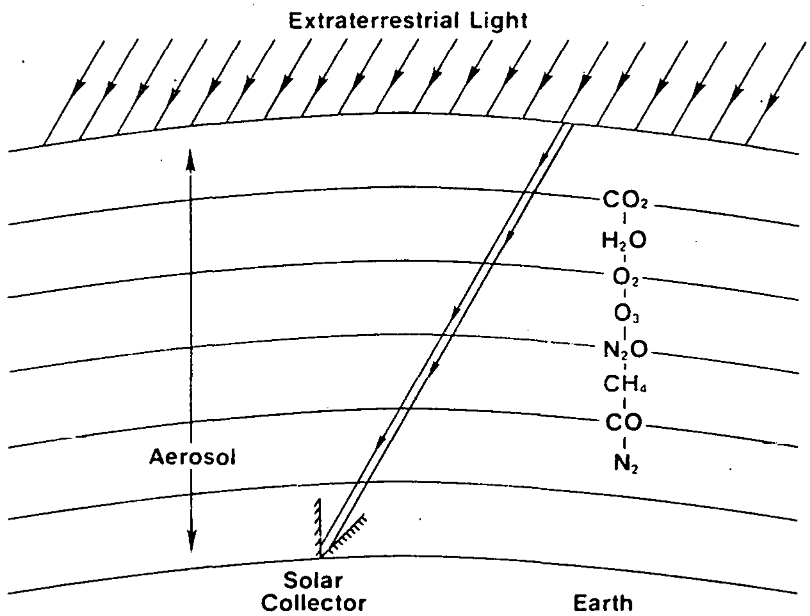

Figure 1. A Representation of the Atmospheric Composition of the SOLTRAN Insolation Model

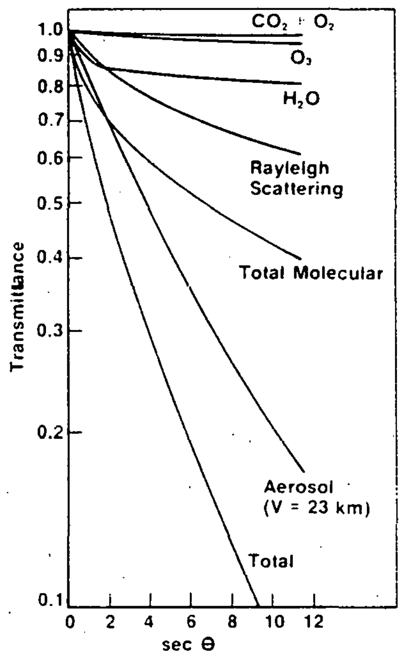

Figure 2. SOLTRAN Model Results Showing Transmittance Versus the Secant of the Solar Zenith Angle for a Midlatitude Summer Atmosphere

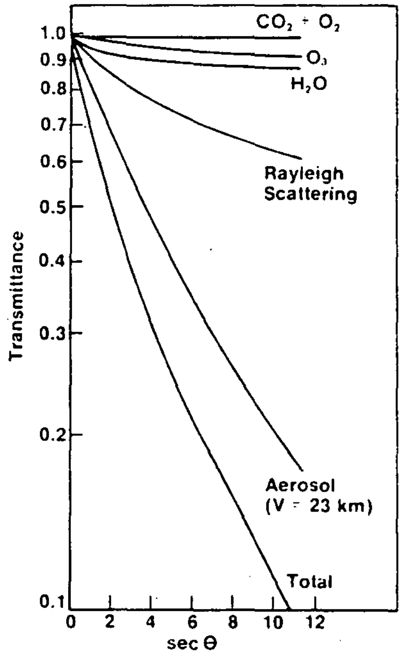

Figure 3. SOLTRAN Model Results Showing Transmittance Versus the Secant of the Solar Zenith Angle for a Subarctic Winter Atmosphere

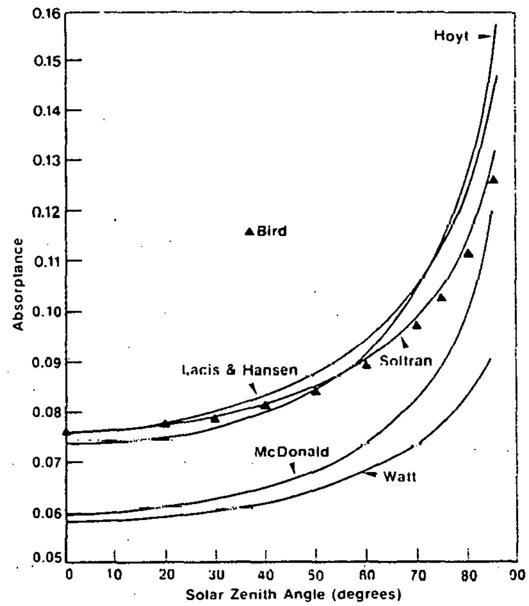

Figure 4. A Comparison of the Absorptance Due to 0.42 cm of Water Vapor for Several Attenuation Models

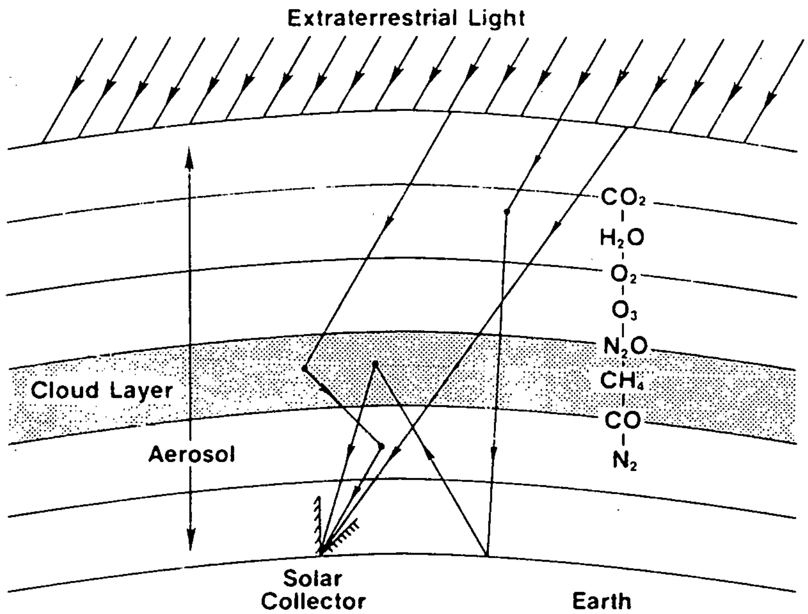

Figure 5. A Representation of the Methods and Capabilities of the Monte Carlo Light Transport Model

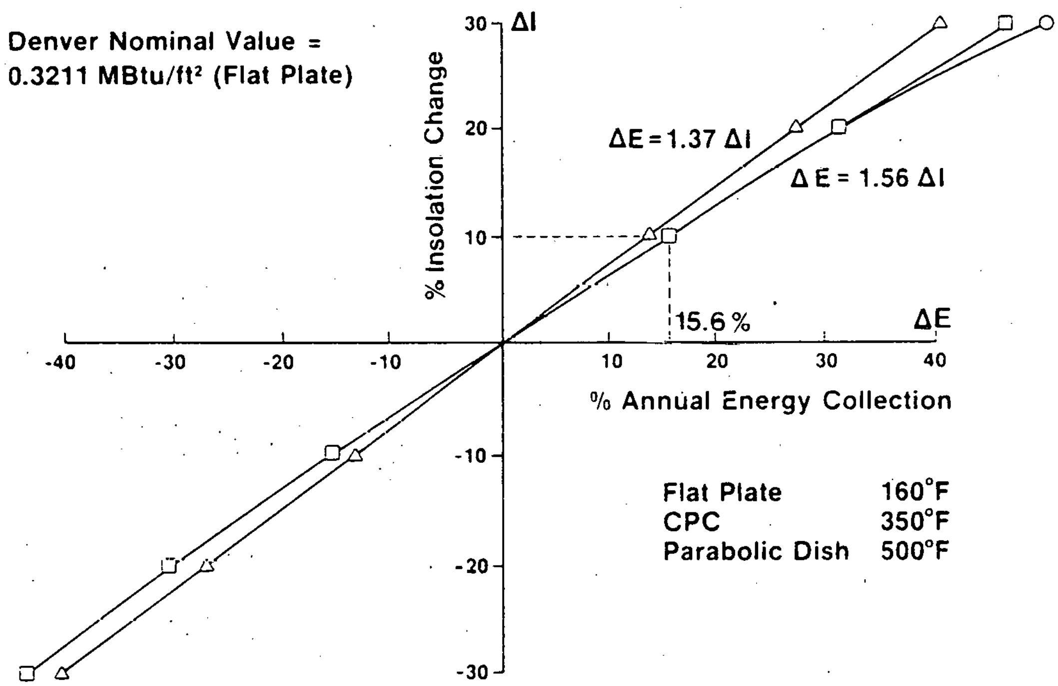

Figure 6. Variability in Annual Energy Collection for a Constant Avg. Operating Temperature Due to Changes in Insolation for Denver, Colorado

Figure 6 is a plot of the percentage of insolation uncertainty versus the percentage of predicted annual energy collection. This figure illustrates the design sensitivity of a flat plate, a concentrating parabolic collector, and a parabolic dish collector to insolation input. There is a near linear relationship with a 10% change in insolation causing nearly a 16% change in predicted annual collected energy. If these data are now used to calculate the cost penalties that uncertainties in insolation estimates can cause, the results shown in Fig. 7 are arrived at. These data show a nonlinear relationship with underestimates in insolation producing severe cost penalties.

The system design, performance, and cost model used to generate these results was the SERI PROSYS model, developed by the SERI Industrial Process Heat Program.* The 0% insolation point, Figs. 6 and 7, represents the "Nominal" or assumed correct insolation data, which is actually the SOLMET database [10]. The site chosen was Denver, Colorado. The results for insolation values of ± 10%, ± 20%, etc., are indicative of the predicted system performance and cost change, if the system were redesigned (variable system siting) using insolation levels of ± 10%, ± 20%, etc., of the nominal insolation levels. The SERI Energy Resource Assessment Branch and the SERI Systems Analysis Branch will expand such studies to include various sites, various systems, and various system models. The goal will be to establish a required/recommended accuracy for insolation data and models and the uncertainties in system performance and cost caused by insolation uncertainties.

CURRENT AND FUTURE AEROSOL MEASUREMENTS

The most common measurement made on aerosols, in conjunction with insolation measurements, is that of atmospheric turbidity. The turbidity is defined as the optical depth due to aerosols through a vertical column in the atmosphere. This measurement is usually made with a device called a sun photometer in a spectral band where there is no molecular absorption. The photometer is first calibrated using an extrapolation method to determine its response to the extraterrestrial insolation. Any reduction from this extraterrestrial response value can then be attributed to aerosol attenuation and Rayleigh scattering. A known value of Rayleigh scattering is subtracted to obtain the aerosol optical depth. Refer to Ref. 11 for details on one type of instrument of this kind. Careful attention to accuracy in these measurements has often not been adhered to.

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*Brown, K. C., S. Stadjuhar, D. Hooker, and R. West, "End Use Matching for Solar Industrial Process Heat," Solar Energy Research Institute, SERI/TR-34-091, in preparation.

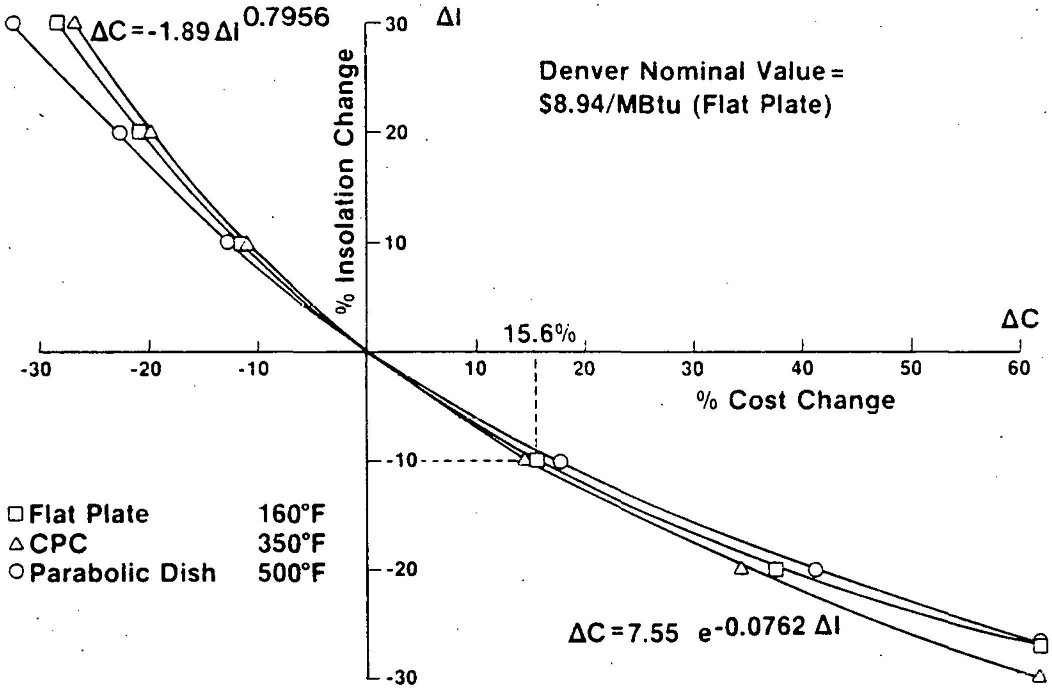

Figure 7. Changes in Collector Cost Due to Changes in Insolation for Constant Avg. Operating Temperatures in Denver, Colorado

Other aerosol measurements that are made less often than turbidity measurements and in conjunction with solar insolation measurements include aureole or circumsolar measurements, LIDAR measurements, and particle size distribution and complex refractive index measurements.

At present, there is a real need for improved methods and instrumentation for characterizing aerosols in conjunction with insolation measurements. Probably the greatest need is for an inexpensive and automated instrument to measure atmospheric turbidity. An automated circumsolar measuring instrument is also desirable. With this instrument one could possibly extract particle size distribution. The use of the circumsolar instrument in conjunction with a multichannel turbidity meter might make it possible to detect subvisual cirrus clouds, which is of great interest to solar workers. The need for monitoring the volcanic layer near 20 km altitude separately from turbidity measurements has not been firmly established yet, but may prove to be important as research continues. An important consideration in many solar instruments is that they are designed for possible use in a national solar network. This means that they need to be automated, reliable, and fairly inexpensive.

CONCLUSION

A brief description of SERI's involvement in areas related to atmospheric studies has been presented. This DOE-sponsored program is called the Insolation Resource Assessment Program, managed and conducted by the SERI Energy Resource Assessment Branch. A discussion of initial insolation and atmospheric modeling results has shown the relative attenuation of the integrated, broadband (thermal), direct insolation by the various atmospheric constituents. Aerosols appear to be the greatest attenuator of the broadband (thermal) direct beam insolation, although the Rayleigh scattering of the molecular atmosphere and water vapor absorption are significant attenuators. The atmospheric CO_2, O_2, and ozone are minor attenuators. The importance of the atmospheric aerosols to insolation/solar energy demonstrates a need to characterize and measure them. This may require improved instrumentation and possibly an actual national network of instrumentation. This will be more definitely established by additional research. An initial determination of the impact of uncertainties in the amount of insolation on solar thermal system performance and cost has shown the need for accurate measurements and estimates of insolation.

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